THE RELATION BETWEEN THE FAT-CONTENT AND THE ELECTRICAL CONDUCTIVITY OF MILK.

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Milk consists of water containing substances in solution, in the colloidal state, and in suspension. The electrical conductivity of milk is due to the presence of ionised salts among the substances in solution. The colloidal and the suspended matter, the protein and the fat, do not contribute appreciably to the transport of electricity. These substances, in fact, depress the conductivity, for they displace a certain amount of conducting material.

The effect of protein on the conductivity of milk has been studied by Jackson and Rothera (1913). They removed the proteins from separated milk by dialysis, and found that each gram of protein in 100 cc. of the separated milk depressed the electrical conductivity by 2·76%.

The effect of fat on the conductivity is shown by the figures given by Taylor (1913). He found, as an average of five experiments, that the removal of 5% of fat from milk caused an increase of electrical conductivity of 11·4%. This increase of conductivity is more than twice as great as that which would be accounted for by the increased concentration of electrolyte due to the removal of the fat. The excess is ascribed by Taylor to the removal of the mechanical obstruction which the fat-globules may offer to the movement of the ions.

The object of the present work was to investigate more closely the relation between the fat-content of cows' milk and its electrical conductivity.

It has been found that, in a given sample of milk, the depression of conductivity is directly proportional to the fat-content; but that, in different samples of milk, the removal of equal amounts of fat does not lead to equal increments of conductivity. Various other properties of the milk have been examined in the endeavour to account for this difference between samples, but no definite correlation has been found.

1. *Relation between the fat-content of a sample of milk and its electrical conductivity.*—Mixtures of the same sample of milk with different percentages of fat were prepared by spinning the samples in a centrifuge to remove as much of the fat as possible, and mixing various proportions of the spun and the whole milk. The conductivities of these mixtures of known fat-content were determined.

The percentages of fat in the spun and whole milk were determined by the Röse-Gottlieb method; the percentages of fat in the various mixtures were obtained by calculation. The results have errors of not more than 2%.

The electrical conductivities were determined at 25°C., by the Kohlrausch method; a Wolff's Wheatstone-bridge was used, with a telephone as a null instrument The determinations were made in a conductivity-vessel provided with vertical electrodes. The measurements obtained were concordant to 0·5%. The details of these methods are given in a previous paper (Wardlaw, 1917).

As the effect of the fat on the conductivity is probably related more closely to the volume occupied than to the weight in a given quantity of milk, some preliminary determinations were made of the density of the fat in the samples examined; from these figures, the volumes can be calculated.

The density of the milk-fat was calculated from the densities of the spun and the whole milk. The figures obtained are given in the accompanying Table.

TABLE i.

Density of fat removed from cows' milk by spinning.

Sample.	Density of milk.		Percentage of fat.		Density of fat.
	Spun.	Whole.	Spun.	Whole.	
5	1·0312	1·0349	3·51	0·19	0·933
7	1·0307	1·0347	3·98	0·16	0·938
8	1·0308	1·0352	3·78	0·17	0·923
9	1·0306	1·0349	4·03	0·15	0·933
10	1·0312	1·0354	3·80	0·18	0·929
11	1·0310	1·0351	3·73	0·17	0·927
12	1·0303	1·0347	4·05	0·17	0·922
13	1·0308	1·0352	3·70	0·16	0·921
21	1·0317	1·0351	3·51	0·13	0·934
Mean					0·929

The determinations of density were made as described in a previous paper (Wardlaw, *loc. cit.*), water at 25°C. being taken as standard. The results have an error of about 1 in 10,000.

If the two errors are maximal and fall in opposite directions, the calculated density of the fat will have a possible error of about 2% The actual values obtained, as shown above, have an extreme range of rather less than this, from 0·921 to 0·938, and the variation from the mean is less than 1%.

The above results show that the densities of the fat removed by spinning from the samples of milk examined varied between 0·921 and 0·938; 0·93 has been taken as the mean value in the subsequent calculations. This value agrees well with that obtained by previous investigators (Fleischmann, 1885).

The following Table shows the percentages of fat and electrical conductivities (K) of various mixtures in whole and spun milk in the case of different samples, and the ratios of the decrements of conductivity to the corresponding increments of fat-content.

If the decrement of conductivity is directly proportional to the increment of fat, these ratios will be constant for each sample of milk.

TABLE ii.

Relation between electrical conductivity and fat-content of individual samples of cows' milk.

Sample.	Percent. of fat by vol.	Increment of fat.	$K \times 10^{-3}$.	Decrement of $K \times 10^{-2}$	$\frac{D.K \times 10^{-3}}{D.Fat.}$
1	3·75	2·60	4·72	2·9	1·1
	3·42	2·27	4·76	2·5	1·1
	3·12	1·97	4·79	2·2	1·1
	2·85	1·70	4·83	1·8	1·15
	2·60	1·45	4·85	1·6	1·1
	2·38	1·24	4·87	1·4	1·1
	2·19	1·04	4·88	1·3	1·25
	1·15	0	5·01	0	
2	0·29	0	5·43	0	
	1·57	1·28	5·30	1·3	1·0
	2·05	1·76	5·25	1·8	1·0
	2·45	2·16	5·23	2·0	0·95
	2·76	2·47	5·19	2·4	1·05
	2·98	2·69	5·18	2·5	1·0
	3·59	3·30	5·15	2·8	0·85
	4·01	3·72	5·06	3·7	1·05
6	0·23	0	5·38	0	
	1·78	1·55	5·26	1·2	0·8
	2·42	2·19	5·20	1·8	0·85
	2·80	2·57	5·18	2·0	0·8
	3·38	3·15	5·15	2·3	0·75
7	0·17	0	5·40	0	
	1·65	1·48	5·28	1·2	0·8
	2·18	2·01	5·26	1·4	0·7
	3·02	2·85	5·20	2·0	0·7
	3·53	3·35	5·18	2·2	0·65
	4·28	4·11	5·10	3·0	0·7

The values of K in this Table have a possible error 20 to 50 times that of the corresponding measurements of conductivity. The above figures show that the ratio of decrement of conductivity to increment of fat is constant to within the limit of error of the determinations for the samples of milk examined.

From these results, it will be seen that, for a given sample of milk, the depression of conductivity is directly proportional to the percentage of fat.

2. *Relation between fat-content and conductivity of different samples.*—The above figures also indicate, however, that the depression of conductivity due to a given increase of fat-content is not the same for different specimens of milk. To confirm this observation, a number of determinations have been made of the percentage-decrease of conductivity of spun milk due to the addition of 1% of fat. These figures are given in the last column of the following Table.

TABLE iii.

Percentage-depression of electrical conductivity due to the addition of 1 c.c. of fat to different samples of cows' milk.

Sample	Percent. of fat by vol.	D. Fat.	D. K × 10^{-3}.	DK × 10^{-2}.	DK% for 1 c.c. fat.
1	3·75		4·72		
	1·15	2·60	5·01	2·9	2·25
2	4·01		5·06		
	0·29	3·72	5·43	3·7	1·8
3	3·87		4·84		
	0·19	3·68	5·10	2·6	1·3
4	4·15		5·07		
	0·18	3·97	5·37	3·0	1·4
5	3·78		5·10		
	0·23	3·55	5·41	3·1	1·65
6	3·38		5·15		
	0·23	3·15	5·38	2·3	1·35
7	4·28		5·10		
	0·17	4·11	5·40	3·0	1·35
8	4·06		5·11		
	0·18	3·88	5·42	3·1	1·5
9	4·33		5·07		
	0·16	4·17	5·37	3·0	1·35
10	4·09		5·08		
	0·19	3·89	5·44	3·6	1·7
11	4·01		5·09		
	0·18	3·83	5·37	2·8	1·35
12	4·36		5·05		
	0·18	4·17	5·36	3·1	1·4
13	3·98		5·07		
	0·17	3·81	5·39	3·2	1·55
14	3·92		5·08		
	0·20	3·72	5·41	3·3	1·65
15	3·84		4·99		
	0·16	3·68	5·35	3·6	1·8

TABLE iii.—(*continued*).

Sample.	Percent. of fat. by vol.	D. Fat.	D.K × 10^{-3}.	D.K × 10^{-2}.	D.K % for 1 c.c. fat.
16	3·98		5·05		
	0·14	3·84	5·33	2·8	1·35
17	4·39		5·02		
	0·17	4·11	5·32	3·0	1·4
18	3·70		5·01		
	0·17	3·53	5·42	4·1	2·15
19	3·96		5·21		
	0·15	3·81	4·93	2·8	1·4
20	3·97		5·81		
	0·12	3·85	5·47	3·4	1·5
21	3·65		5·37		
	0·14	3·51	5·71	3·4	1·7
22	3·59		5·43		
	0·18	3·41	5·72	2·9	1·5
23	3·86		5·49		
	0·15	3·71	5·83	3·4	1·6
24	3·70		5·46		
	0·14	3·56	5·83	3·7	1·8
25	3·80		5·48		
	0·15	3·65	5·85	3·7	1·75
26	4·10		5·51		
	0·13	3·97	5·89	3·8	1·65
27	3·45		5·88		
	0·16	3·29	6·21	3·3	1·6
28	3·96		5·34		
	0·15	3·81	5·67	3·3	1·55
29	3·75		5·50		
	0·17	3·58	5·81	3·1	1·5
30	3·72		5·48		
	0·16	3·56	5·78	3·0	1·45
31	3·55		5·55		
	0·16	3·37	5·89	3·4	1·7
32	3·67		4·47		
	0·16	3·51	5·81	3·4	1·65
Mean					1·58

The figures in the above Table show that 1 c.c. of fat in 100 c.c. of milk depresses the conductivity 2·3 to 1·3% of the value for spun milk in the samples examined, the mean depression being 1·58%. The effect of fat on the conductivity in these cases is thus 30 to 120% greater than can be accounted for by the amount of conducting material displaced.

It was thought that this variable effect upon the conductivity might be due in some way to the method of removal of the fat from the milk. The milk might be concentrated slightly by evaporation during the process of spinning in the centrifuge. The conductivity of the spun milk would then be greater than could be accounted for by the removal of the fat. Or, substances other than fat might be removed by spinning. In this way also the electrolytes of the spun milk might become more concentrated, and the effect of the removal of the fat would be exaggerated.

To test the first of the above suppositions, the conductivity of samples of milk which had been spun covered to prevent evaporation was compared with the conductivity of samples spun uncovered in the ordinary way. The results obtained are given below.

Electrical conductivity of milk after spinning in covered and uncovered tubes.

Sample.	Conductivity.	
	Covered.	Uncovered.
3	5·08	5·08
4	5·37	5·35
5	5·39	5·40

These results show that there is no appreciable increase of conductivity due to the concentration of the milk by evaporation during spinning.

To test the second hypothesis, the amounts of total solid matter as well as of fat in the milk were determined. The following Table gives the weights of fat and of total solids in 100 c.c. of milk before spinning, and in the volume obtained after spinning (100 c.c. less volume of fat).

TABLE IV.

Weights of fat and of total solid matter removed from 100 c.c. of milk by spinning in a centrifuge.

Sample.	Fat in 100 c.c.		Solids in 100 c.c.		Wt. from 100 c.c.		Solids.
	Whole.	Spun.	Whole.	Spun.	Fat.	Solids.	Fat.
8	3·78	0·17	12·70	8·91	3·61	3·79	1·05
9	4·03	0·15	12·76	8·54	3·88	4·22	1·09
10	3·80	0·18	12·72	9·07	3·62	3·65	1·01
11	3·73	0·17	12·66	8·94	3·56	3·72	1·05
12	4·05	0·17	12·95	8·82	3·88	4·13	1·06
13	3·70	0·16	12·60	8·95	3·54	3·65	1·03
14	3·65	0·19	12·58	8·92	3·46	3·66	1·06
15	3·57	0·15	12·88	8·95	3·42	3·83	1·12
16	3·70	0·13	12·72	8·92	3·57	3·80	1·06
17	4·08	0·16	13·00	8·96	3·82	4·04	1·06
18	3·44	0·16	12·39	8·99	3·28	3·40	1·04
20	3·80	0·11	12·85	9·00	3·69	3·85	1·04
21	3·39	0·13	12·40	9·01	3·26	3·39	1·04
22	3·44	0·17	12·45	9·09	3·27	3·36	1·03
23	3·70	0·14	12·72	8·97	3·56	3·75	1·05
24	3·54	0·13	12·56	9·00	3·41	3·56	1·04
25	3·64	0·14	12·57	9·05	3·50	3·52	1·01
26	3·92	0·12	12·99	9·00	3·80	3·99	1·05
27	3·31	0·15	12·01	8·85	3·16	3·16	1·00
28	3·79	0·14	12·80	8·86	3·65	3·94	1·08
29	3·59	0·16	12·59	9·08	3·43	3·51	1·02
30	3·55	0·15	12·51	9·00	3·40	3·51	1·03
31	3·40	0·15	12·35	8·96	3·25	3·39	1·04
32	3·51	0·15	12·57	9·06	3·36	3·51	1·05

The above figures show that a certain amount of material other than fat is removed from milk by spinning. This is the material adsorbed by, and adherent to, the fat-globules, and as would be expected from the rather indefinite nature of its association with the fat, its amount is rather variable, ranging from 12% to 1% of the weight of fat removed. If this material be assumed to have the average density of the solids other than fat of milk, 1·6, then the volume occupied by it will be only 0·6 to 7% of the total volume removed. This increase of volume is quite insufficient to account for the excess of the effect of the fat on the conductivity over the volume-effect (30-120%).

3. *Effect of degree of subdivision of fat.*—It was thought that some light might be thrown on the variable effect of fat on the

conductivity of milk by examining the relation between this effect and the number of fat-globules in a given volume of fat.

The effect of non-conducting suspended matter on the conductivity of electrolytes has been studied by Oker-Blom (1900). He determined the conductivity of suspensions of sand in jellies made up with salt solutions, and came to the conclusion that the size of the particles (between 2 and under 0·5 mm.) made no difference to their effect on the conductivity, but that the sand depressed the conductivity less when uniformly distributed through the jelly than when collected into one layer. These conclusions are to a certain extent contradictory, however, as the difference between the first and second cases is mainly one of aggregation. Further, the range of size of particles examined in the first case was not very great.

The sizes of the fat-particles even in one sample of milk vary enormously. But each sample contains a certain average size and number of particles in a given volume, and well-defined differences exist between the sizes and numbers for samples of different origin. Strippings, for instance, contain larger fat-globules than first milk, and the milk of Jersey cows contains larger particles than the poorer milk of Shorthorn cows.

The number of fat-globules in the milk was counted by the method of Babcock (1886) as modified by Shaw and Eckles (1909). One volume of milk is diluted to 50 with water. The mixture is drawn up into capillary tubes, the internal diameters of the tubes are measured, and the numbers of globules in a known length are counted. From the figures obtained, the numbers of globules in a known volume of the undiluted milk may be calculated. The measurements are made with an ocular micrometer. The workers quoted made the optic measurements with the capillaries immersed in glycerine. It was found in the present work, however, that owing to the differences between the refractive index of glycerine and that of glass, the values of the diameter of the capillaries measured in this way were too high. The present measurements, therefore, were made with the tubes immersed in a solution of chloral hydrate in glycerine (7 : 1). This solution has a refractive index of 1·508, which is

very close to that of the glass used. The measurements were checked by weighing the amount of mercury contained in a known length of the tube. The accompanying figures show that the optical measurements of diameter agree well with those calculated from the weights.

Tube.	Weight of Hg.	Length.	Diameter	
			from weight.	optically.
1	1·35 mg.	13·57 mm.	0·097 mm.	0·096 mm.
2	1·075 ,,	17·35 ,,	0·0745 ,,	0·0735 ,,
3	0·955 ,,	16·15 ,,	0·74 ,,	0·072 ,,
4	1·22 ,,	22·2 ,,	0·071 ,,	0·072 ,,

These figures show that the results obtained by the two methods are concordant to within their limits of error.

In the following Table are shown the ratios of percentage of fat to the percentage-decrease of conductivity, and the numbers of fat-globules in 1 cu.mm for different samples of cows' milk.

TABLE V.

Degree of subdivision of milk-fat and its effect on the electrical conductivity.

Sample.	Fat in 100 c.c. D.K% for 1% fat.	Globules per cu.mm, milk $\times 10^{-6}$	Globules per cu.mm. fat $\times 10^{-4}$.
19	1·36	1·92	4·85
20	1·36	1·94	4·86
21	1·71	1·96	5·40
22	1·44	1·72	4·65
23	1·53	1·79	4·51
24	1·73	1·98	5·20
25	1·69	2·02	5·17
26	1·58	1·89	4·47
27	1·57	2·27	6·38
28	1·49	2·10	5·15
29	1·45	2·02	5·22
30	1·42	1·95	5·09
31	1·65	1·77	4·84
32	1·62	2·12	5·61

As will be seen from the above figures, no simple relation ap-

pears to exist between the depression of conductivity due to 1 c.c. of fat in 100 c.c. of milk and the average number of globules into which this amount of fat is divided, or the average size of the globules. The degree of subdivision of the fat thus does not seem to influence its effect on the conductivity in excess of the effect due to the volume displaced.

4. *The relation between the increase of viscosity due to the fat of milk and its effect on the electrical conductivity.*—The electrical conductivity of a solution of electrolytes depends on the velocity and concentration of its ions. One factor which determines the velocity of the ions is the resistance which the liquid of the solution opposes to their movement. In the case of aqueous solutions of salts only, this resistance is measured by the viscosity. In the case of systems which are not homogeneous, however, the viscosity of the system as a whole is not a measure of the resistance offered to the passage of ions. The addition of gelatine to a salt solution, for example, may increase the viscosity enormously, while the resistance to the movement of ions, as measured by the conductivity, is hardly affected. The system is no longer homogeneous, but consists of two phases.

Milk is such a heterogeneous system, and contains at least three phases. No simple relation is to be expected, therefore, between the viscosity of milk as a whole and its electrical conductivity. It was thought, however, that these two properties might be connected in some regular manner which would explain the disparity between the volume occupied by the fat of milk and its effect on the conductivity.

In the following Table are shown the effect of the removal of measured amounts of fat on the conductivity and viscosity of milk. The viscosities were measured in an Ostwald viscosimeter at 25°C. The values given are those compared with water as unity. The results have a maximum relative error of 1%.

TABLE VI.

Effect of fat on conductivity and viscosity of milk.

Sample.	Decrement of fat.	Increment of K.	Viscosity. Whole.	Viscosity. Spun.	DK% / DFat%	DV% / DFat%
28	3·92	3·3	1·96	1·55	1·38	1·07
29	3·69	3·1	1·74	1·59	1·35	1·03
30	3·83	3·0	1·84	1·64	1·32	1·03
31	3·49	3·4	1·86	1·59	1·53	1·05
32	3·61	3·4	1·81	1·61	1·51	1·03

The above figures show that in these samples of milk a decrease of 1 gm. of fat in 100 c.c. diminished the viscosity from 3 to 7%. The corresponding increases of conductivity, however, are from 30 to 50% above the values due to the volume occupied by the fat. The diminution of viscosity is thus quite insufficient to account for the discrepancy between the volume occupied by the fat and its effect on the conductivity. It will be seen, too, that the increase of conductivity is not proportional to the decrease of viscosity.

These results also indicate that, in the samples of milk examined, the effect exerted on the conductivity by 1% of fat by volume is as variable as the effect exerted on the conductivity, and does not show that constancy which Taylor (*loc. cit.*) found in the samples examined by him.

5. *The behaviour of fat-globules in an electric field.*—If the fat-globules of milk carry an electric charge, they may retard the movement of ions in their vicinity, and in this way be responsible for the variable effect that fat exerts on the conductivity in addition to the effect due to the volume displaced. The attempt was made to observe whether the fat-globules were charged by placing milk in a shallow cell less than 1 mm. deep, provided with platinum electrodes (Chick and Martin, 1912). A current was passed between the electrodes, and the fat-globules were watched under the microscope. No movement was observed with a fall of potential below about 3 volts per cm. With higher voltages, bubbles of gas were formed at the electrodes, and caused movement of the globules mechanically. These experiments do not show conclusively that the fat-globules of milk

are not charged electrically. They indicate, however, that any charge carried must be small; much smaller, for example, than that carried by the particles of a suspension of coagulated protein, which show very evident movement in an electric field under conditions similar to those described.

SUMMARY.

(1). Removal of fat from milk increases the electrical conductivity.

(2). In a given sample of milk, the increase of conductivity is directly proportional to the volume of fat removed.

(3). The increase of conductivity due to the removal of a given amount of fat is not the same, however, in different samples of milk. The average increase of conductivity due to the removal of 1% by volume of fat is 1·5%.

In conclusion, I wish to express my indebtedness to Sir Thomas Anderson Stuart, in whose laboratory this work was done.

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